

5 This invention relates to rare-earth metal containing electron-injecting electrodes which are particularly effective for use with organic LED devices used in electroluminescent structures and which may in particular be formed as transparent electrodes for use in transparent or surface emitting OLEDs.

Since the first report of high efficiency organic light-emitting devices (OLEDs), OLEDs have attracted extensive interest because of their enormous potential for applications in full-color flat panel displays. Device performance of OLEDs strongly depends on a balanced injection of holes and electrons into the emitting layer from the anode and the cathode. It is generally believed that lowering the injection barrier between the electrodes and the organic medium will facilitate effective carrier injection. Intensive effort has been expended on modifying and optimizing the cathode materials to establish efficient electron injection into the adjoining organic layer, such as using low work function metals or composites, doping cathode or organic layers, or inserting an insulating layer at the metal/organic interface.

Ultrathin lithium fluoride (LiF) with an overlaying aluminum film is a commonly used high-performance cathode, which significantly enhances electron injection by liberating the low work-function metal Li via LiF dissociation in the coexistence of Al, LiF, and tris-(8-hydroxyquinoline) aluminum (Alq₃). However, no noticeable dissociation or reaction between LiF/Al occurs in the absence of Alq₃, thus limiting its use for OLED employing other emissive organic materials. It is therefore

highly desirable to provide a material, which has a low work function and yet is applicable in a wide range of organic electronic/optoelectronic devices.

Furthermore, in a fundamental organic LED structure, organic layers in the OLEDs may be deposited on glass with transparent anodes (usually indium tin oxide, ITO) and capped by reflective metal cathodes. These kind of devices are hereinafter referred as bottom emitting (BE) OLEDs. However, for some applications (e.g. active matrix OLEDs), it is necessary to fabricate a surface-emitting (SE) OLED structure on opaque substrates (e.g. silicon based electronics driver and pixel switching elements). Thus, it is highly desirable to develop high performance and transparent cathodes that can be conveniently deposited on organic materials.

SUMMARY OF INVENTION

It is an object of the present invention to provide a transparent electron-injecting electrode for use with an organic electroluminescent (EL) device.

This object is achieved in an organic EL device containing a transparent electron-injecting electrode, the electrode comprising a rare-earth metal or its alloy formed by co-evaporation with a conductive material.

It is another object to the present invention to provide an effective electron-injecting electrode for an organic EL device.

This object is achieved in an organic EL device containing a tri-layer cathode structure, comprising:

- a) a fluoride layer contacting the electroluminescent layer;
- b) a rare-earth metal layer contacting the fluoride layer;
- c) a conductive layer contacting the rare-earth metal layer; and
- d) the thickness of the fluoride layer being selected so that the tri-layer acts an electron injecting contact, the tirlayer providing stability against atmospheric

corrosion.

BRIEF DESCRIPTION OF THE DRAWINGS

Some embodiments of the invention will now be described by way of example

5 an with reference to the accompanying drawings, in which:

Fig.1 is a schematic diagram of the basic structure of an organic LED,

Fig.2 is a schematic diagram of an organic LED according to an embodiment of the present invention.

Fig.3(a) shows the current density as a function of operating voltage for an
10 embodiment of the invention and examples of the prior art for comparison,

Fig.3(b) shows the luminance as a function of operating voltage for an embodiment of the invention and examples of the prior art for comparison.

Fig.4 shows the luminance and current density as a function of operating voltage for three embodiments of the invention with varying cathode thickness together
15 with one example of the prior art for comparison,

Fig.5 is a plot showing power efficiency as a function of current density for an embodiment of the invention and two examples of the prior art for comparison,

Fig.6(a) is a plot of current density and surface emitted luminance and total luminance at 7V as a function of cathode thickness for an embodiment of the
20 invention,

Fig.6(b) is a plot of current efficiency against cathode thickness for an embodiment of the invention,

Fig.7 is a plot showing device characteristics for other rare-earth metal cathodes,

Fig.8 shows device characteristics using a trilayer cathode in accordance with an
25 embodiment of the invention,

Fig.9 is a plot of the operational stability (ie electroluminescence versus

operating time) of an organic LED according to an embodiment of the present invention, and

Fig.10 is a plot of device characteristics using different trilayer structures.

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DETAILED DESCRIPTION OF THE INVENTION

Referring firstly to Fig. 1, an organic EL device 10 has, in order, a substrate 12, a hole-injecting anode 14, an organic layer structure 16, and an electron-injecting cathode 18.

Substrate 12 is electrically insulated and can be either optically transparent (e.g. glass or plastic foil) or opaque (e.g. semiconducting materials or ceramics). For viewing the EL emission through the substrate, or through both sides of device, a glass substrate or a plastic foil is used. For applications where the EL emission is viewed through the top electrode, opaque semiconductor and ceramic wafers can be used.

Hole-injecting anode 14 injects holes into the organic EL layer when this anode is positively biased. The anode 14 is formed of a conductive and optionally transmissive layer. If it is desired to view the EL emission through the substrate, layer 14 should be transparent. For applications where the EL emission is viewed through the top electrode, the transmissive characteristic of the layer 14 is immaterial, and therefore any appropriate materials such as metals or metal compounds having a work function greater than 4.1 eV can be used. Possible metals include gold, iridium, molybdenum, palladium, and platinum. If the anode should be transmissive, suitable materials can be selected from the group of metal oxides, including indium-tin oxide, aluminum- or indium- doped zinc oxide, tin oxide, magnesium-indium oxide, nickel-tungsten oxide, and cadmium-tin oxide. The desired metals and metal oxides can be deposited by evaporation, sputtering, laser ablation, and chemical vapor

deposition.

Organic layer structure 16 either has a single layer acting as a light emitter or may be a multilayer structure, including a light emitter and carrier confinement layers. For instance, a useful structure includes a diamine layer and an undoped or doped Alq layer, as described in U.S. Pat. Nos. 5,294,869, and 5,151,629. Other suitable materials used for light emitters include poly(9,9-dioctylfluorene) (PFO), PFO copolymers, and 9,10-di-(2-naphthyl) anthracene (DNA). Organic structure 16 can be prepared by thermal evaporation or spin-coating from a solution.

Top electron-injecting cathode 18 acts as a transmissive electron injector that injects electrons into the organic EL layer when the cathode is negatively biased. The cathode is formed of a rare-earth metal or by co-evaporation of a rare-earth metal and a conductive metal. Suitable rare-earth metals include lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, and ytterbium. Suitable conductive metals include gold, silver, nickel, palladium, and platinum.

Referring to Fig.2, an organic EL device 20 according to an embodiment of the invention has, in order, a substrate, 22, a hole-injecting anode 24, an organic layer structure 26, an electron-injecting cathode 28. The top cathode includes a fluoride layer 28a, a rare-earth metal layer 28b, and a conductive overlayer 28c.

Substrate 22 is electrically insulating and can either be a bare glass substrate or plastic foil. The light transmissive property of a glass substrate or a plastic foil is desirable for viewing the EL emission through the substrate.

Hole-injecting anode 24 is either a transparent conducting oxide or a thin metal layer with sufficient optical transparency to allow light to traverse through this layer and the substrate. Suitable metal oxides indium-tin oxide, aluminum- or indium-doped zinc oxide, tin oxide, magnesium-indium oxide, nickel-tungsten oxide, and

cadmium-tin oxide. Suitable metals include gold, silver, nickel, palladium, and platinum.

Organic layer structure 26 either has a single layer acting as a light emitter or a multilayer structure, including a light emitter and carrier confinement layers. The composition of this layer is similar to that described for organic layer 14 in FIG. 1.

Electron-injecting cathode 28 includes a thin fluoride layer 28a, a rare-earth metal layer 28b, and a thick conductive overlayer 28c. The fluoride layer can be selected from the group of alkali fluorides and alkaline earth fluorides. The rare-earth metal layer includes lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, and ytterbium. An effective electron injector can be formed as an ultra-thin fluoride layer that is in contact with a rare-earth metal in order to liberate very low work function metal atoms at the contact, reducing the electron injection barrier into organic medium. The conductive overlayer can be selected from the group of elemental metals, metal alloys, and other conductive materials. This conductive overlayer provides stability against atmospheric corrosion.

EXAMPLES

The following examples are presented for a further understanding of the invention. For purpose of brevity, the materials and the layers formed will be abbreviated as given below:

- ITO : indium-tin oxide (anode)
- NPB : α -naphthylphenylbiphenyl diamine
- Alq : tris-(8-hydroxyquinoline) aluminum
- Yb:Ag : ytterbium:silver at a ratio of 2.5:1 by volume (cathode)

Example 1

An organic EL device according to an embodiment of the invention was constructed in the following manner.

- a) a transparent anode of ITO-coated glass was ultrasonicated in a commercial
5 detergent, rinsed in deionized water, and then dried in an oven. The substrate was further subjected to a UV-ozone treatment for 15 minutes;
- b) the substrate was put into a vacuum chamber, and the chamber was pumped down to 5×10^{-6} mbar;
- c) a 72 nm thick NPB hole-transporting layer was deposited on ITO;
- 10 d) a 48 nm thick Alq emitting and electron-transporting layer was deposited on NPB layer;
- e) a 37.2 nm thick Yb:Ag layer was deposited on the Alq layer. All materials were prepared by thermal evaporation from tantalum boats.

15 Example 2

The same materials and processing procedures were employed as described in Example 1, except that the thickness of Yb:Ag was replaced by 24.8nm.

Example 3 corresponds to Examples 1 and 2 except that the Yb:Ag layer has a
20 thickness of 18.6 nm.

Example 4 is a device having a thicker non-transmissive cathode and has the structure ITO/NPB(72nm)/Alq(48nm)/Yb(14.5nm)/Ag(200nm).

25 Fig.3 shows (a) the current density and (b) the luminance of the device of Example 4 as a function of operating voltage and for comparison shows the

characteristics of prior art devices formed with Mg:Ag, LiF/Al and Ag cathodes. Figs.3(a) and (b) clearly show the increased current density and luminance of the device of Example 4 compared with the prior art at any given operating voltage, save for LiF/Al at operating voltages above 9V.

5 Examples 1 to 3 are formed with thin transmissive cathodes and as such can be used as surface emitting (SE) devices. The electrical and optical properties of these devices are shown in Fig.4 which plots current density (left axis) and luminance (right axis) against operating voltage for Examples 1 to 3 and also includes a prior art Mg:Ag device for comparison. For the three SE devices with a Yb:Ag cathode, the
10 highest current density and luminance were obtained when the cathode thickness is 37.2nm. As the Yb:Ag cathode layer becomes thinner, the current density obtained also decreases. This current density decrease is most likely caused by the lower (conductance) of the thinner cathode layer. Luminance of Yb:Ag SE devices also shows a similar trend in that higher luminance can be obtained as the thickness of the
15 Yb:Ag alloy cathode increases.

In the Yb:Ag devices without the reflecting Ag mirror (Examples 1 to 3), the OLEDs were transparent, and light can be emitted through both the top cathode surface and ITO substrate.

Fig.5 shows the power efficiency as a function of current density for the device
20 of Example 4 and prior art Mg:Ag and Ag devices for comparison. Fig.5 clearly shows the improved power efficiency of the device of Example 4.

Fig.6(a) show the surface emitted (SE) luminance, the total luminance and the current density as a function of transparent Yb:Ag cathode thickness at a driving voltage of 7V. As film thickness increases, both SE and total luminance increase with
25 accompanying current density increases. However, while the total luminance considerably increases, the surface emission only slightly increases. This implies that

a large proportion of light cannot pass through the top cathode surface and consequently is reflected backward, giving a smaller SE luminance.

Fig.6(b) shows the current efficiency for both SE and total luminance with thickness variation. The total emitted efficiency increases as Yb:Ag film becomes thicker because of significant reduction of the resistance of Yb:Ag cathode, giving a better electron injection and contact thus higher attainable current density and luminance. However, under the same condition, the current efficiency for surface-emitting devices drops because of absorption, internal reflection of light caused by the thicker Yb:Ag layer.

Example 5 corresponds to Example 4 except that the Yb layer is replaced by other rare-earth metals, Sm, Ce and Ho.

Fig.7 shows the device characteristics of current-voltage-light emission using different rare-earth metal cathodes. Apparently, raising the electron barrier increases the operating voltage. By replacing the Yb cathode (2.6eV) with the high work-function rare-earth metals Sm (2.7eV), Ce (2.9eV) and Ho(3.1eV), both the J-V and L-V curves shift to a higher driving voltage as predicted. This is attributed to the increase in electron injection barrier at the organic/metal interface, and therefore lower electron injection properties of the metal cathode.

Example 6

An organic EL device was constructed in the following manner:

- a) an ITO-coated glass was ultrasonicated in a commercial detergent, rinsed in deionized water, and then dried in an oven. The substrate was further subjected to

- a UV-ozone treatment for 15 minutes;
- b) the substrate was put into a vacuum chamber, and the chamber was pumped down to 5×10^{-6} mbar;
- c) a 72 nm thick NPB hole-transporting layer was deposited on ITO;
- 5 d) a 48 nm thick Alq emitting and electron-transporting layer was deposited on NPB layer;
- e) a 1.3 nm thick cesium fluoride was deposited on the Alq layer;
- f) a 14.5 nm thick ytterbium layer was deposited on the CsF layer; and
- g) a 200 nm thick silver layer was deposited on the Yb layer. All materials were
- 10 prepared by thermal evaporation from tantalum boats.

Example 7 (Prior art)

The same materials and processing procedures were employed as described in Example 6, except that the CsF/Yb/Ag trilayer was replaced by a 200 nm thick

15 Mg:Ag layer with a volume ratio of Mg:Ag = 9:1.

Example 8

The same materials and processing procedures were employed as described in Example 4, except that the cesium fluoride layer was replaced by a lithium fluoride

20 layer or sodium fluoride layer.

The device characteristics of current-voltage-light emission are summarized in Fig.8. Apparently, the insertion of the CsF layer significantly improves the device performance. Both J-V and L-V curves shift to a lower driving voltage. For instance,

25 the driving voltage at a current density of 100 mA/cm^2 of devices with the CsF/Yb, Yb, and Mg:Ag cathodes are 7.15, 7.65V and 11.7V respectively. Similarly, the

voltages to obtain a luminance of 1000 cd/m^2 for the three devices are 5.55, 6.20V and 8.60V respectively. In addition, the turn-on voltage (defined as the voltage required to obtain a luminance of 1 cd/m^2) for the device with the CsF/Yb cathode is reduced to 2.42V, while that for Yb and Mg:Ag cathodes are at 2.95 and 3.75V respectively. Mechanisms responsible for the performance enhancement is attributed to the dissociation of CsF. This dissociation of CsF occurs spontaneously upon addition of a small amount of Yb onto it, and liberates the low work-function Cs, which dopes the electron-transporting layer and reduces the electron injection barrier; resulting in an excellent electron injecting contact. This cathode system can also be effective for almost all types of organic medium, either molecular or polymer based materials, giving a strong evidence that this dissociation is a substrate-independent process.

Example 9

The same materials and processing procedures were employed as described in Example 5, except that the devices were encapsulated. The devices were driven at a constant current density of 20 mA/cm^2 .

Fig.9 exhibits the operational stability of devices with configuration of NPB/Alq/CsF/Yb/Ag tested at 20 mA/cm^2 at room temperature. L_0 for the device was 500 cd/m^2 . The luminance of presented device loses only about 26% after 800h. The reason behind for this long lifetime may be attributed to the abruptly end of oxygen diffusion at the CsF/Al interface, and thus significantly prolongs the degradation of devices and suppresses the growth of dark-spots, as in the case of PFO/CsF/Al or Alq₃/LiF/Al.

Example 10

The same materials and processing procedures were employed as described in Example 6, except that the Yb layer was replaced by a Sm, Ce or Ho layer.

5 The device characteristics using different trilayer cathodes are shown in Fig.10. Upon insertion of the CsF layer at the rare-earth metal/organic interface, the operating voltage of the devices dramatically reduces, as compared to a device with a Mg:Ag cathode. All devices using the trilayer cathode (CsF/Yb, CsF/Sm, CsF/Ho or CsF/Ce) perform almost identically with turn-on voltages of around 2.4eV. This performance
10 improvement is mainly attributed to the release of free Cs metal atoms at the contact, reducing the cathodic barrier. This demonstrates that the trilayer cathode structure can also be effective with the use of other rare-earth metals.

 The invention has been described in detail with particular reference to certain
15 preferred embodiments thereof, but it will be understood that variations and modifications can be effected within the spirit and scope of the invention.